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13. ABSTRACT *(Maximum 200 words)*

This project develops a new method for image acquisition to improve resolution. Ordinarily, a focal plane sensor array is arranged in a rectangular grid at sub-Nyquist spacing, and the array must be dithered to sample the image plane at the Nyquist rate in each dimension. However, the Nyquist rate oversamples the image due to the usually circular support of the diffraction-limited image spectrum. We develop efficient algorithms for optimizing the dithering pattern so that the image can be reconstructed as reliably as possible from a periodic nonuniform set of samples obtained from a dithered rectangular-grid array. Furthermore, we develop efficient reconstruction algorithms that can quickly reconstruct the uniformly sampled image from its nonuniform samples. To support this framework, we derive a reconstruction method that accommodates the shift-variant effects of boundary conditions as well as the effect arising from the need to smooth the image less near edges to reconstruct sharp edges from low-resolution data. The method decomposes the image into two parts, one of which can be computed with FFT's and the other requiring a small matrix inversion. The resulting methods allow faster image acquisition as well as faster reconstructions that contain less noise and fewer artifacts when restoring and superresolving the acquired images.

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Superresolution of Passive Millimeter-Wave Imaging
AFOSR Grant AF-F49620-01-1-0147
Final Report
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1. Objectives

This project develops a new method for image acquisition and processing that will yield higher useful resolution and superresolution capability. One important issue in practical hardware implementations of passive millimeter-wave imaging is the method used to sample the image plane. Ordinarily, a focal plane sensor array has sensors placed in a rectangular grid pattern at sub-Nyquist spacing, and the array must be dithered to sample the image plane at the Nyquist rate in each dimension. However, the Nyquist rate oversamples the image due to the usually circular support of the diffraction-limited image spectrum. Furthermore, due to the relatively large size of the sensors compared to the total array size, boundary effects in the reconstructed image may be problematic especially when the sample spacing near the boundaries is uniformly large. We propose to develop efficient algorithms for optimizing the dithering pattern so that the image can be reconstructed as reliably as possible from a periodic nonuniform set of samples, which can be obtained from a dithered rectangular-grid array. The optimal sampling algorithms will take into account the frequency support of the image, the finite array size, and the goals of high-resolution reconstruction and superresolution. Furthermore, we will develop efficient reconstruction algorithms that can quickly reconstruct the uniformly sampled image from its nonuniform samples. The resulting methods will allow faster image acquisition as well as reconstructions that contain less noise and fewer artifacts when restoring and superresolving the acquired images.

2. Status of Effort

Our efforts have continued to focus on computationally tractable methods for two problems in the restoration of passive millimeter wave (PMMW) imagery - unknown boundaries and the non-stationary nature of images containing edge structures. In both cases, the solution to these problems requires a tremendous increase in the computational burden compared to FFT restoration.

Fast and accurate restorations that account for these issues will not only result in a better dithering pattern selection method. It can also be used to aid in adapting the locations of sensor arrays for particular images. More generally, it will also result in a more efficient and more artifact-free restoration, since the heart of the computational issue is a more tractable restoration method for this structure.

In most restoration problems, the observation equation can be represented or approximated by a finite-support point-spread function (PSF) operating on the original image with additive noise. In such cases, the forward model can be represented by a banded-block-Toeplitz matrix with banded Toeplitz blocks once we incorporate the fact that the boundaries are unknown. We have developed a fast method for solving such systems of equations. The method augments the system to a block-circulant with circulant-blocks system and then uses the concept of generalized displacement rank to find an LU decomposition of the augmented matrix term to solve the original problem.

We have shown that the restoration can be decomposed into a sum of two independent restorations. One restoration is based on a modified FFT-based approach containing the usual boundary artifacts. The other restoration involves a set of unknowns whose number equals that of the unknown boundary values to correct the artifacts in the first restoration. By summing the two, the artifacts are canceled. Because the second restoration has a significantly reduced set of unknowns, it can be calculated very efficiently even though no circular convolution structure exists. We have shown that an easily computed approximation can be made that often eliminates the need for the second restoration. Where greater accuracy is needed, a few iterations of a conjugate gradients algorithm serves to eliminate visual boundary artifacts.

We have also shown that the nonstationary component of a typical image can be separated so that the restoration is decomposed into two restorations - one being the restoration obtained by the approach described in the previous paragraph and the other consisting of a single unknown for each nonstationary point in the image. Because this second restoration involves a much-reduced set of unknowns, it can be solved directly or through a much faster iterative procedure.

The nonstationary restoration approach has been implemented in the quadratic case and proven to work very efficiently. The method has now been extended to nonquadratic penalty functions with great promise. The nonquadratic penalty is locally approximated by a quadratic penalty at each iteration. The quadratic term is identical except at edge locations, and the quadratic algorithm can solve the approximate criterion exactly at each iteration. A proof of global convergence has also been derived.

We have developed a hierarchical approach to selection of the dithering pattern for sub-sampled focal plan array imaging. The method allows for much faster optimization of the dithering pattern. The basic steps of this algorithm were developed for an application in magnetic resonance imaging; the algorithm is being adapted to the PMMW problem.

4. Personnel Supported

Stanley J. Reeves, PI
Ruimin Pan, Graduate Research Assistant

5. Technical Publications

S. J. Reeves, "Fast restoration of PMMW imagery without boundary artifacts," in SPIE Vol. 4719 - Infrared and Passive Millimeter-Wave Imaging Systems: Design, Analysis, Modeling, and Testing (R. Appleby, G. C. Holst, and D. A. Wikner, eds.), (Orlando, FL), pp. 289-295, SPIE - Int. Soc. Opt. Eng. (US), April 2002.

S. J. Reeves, "Fast algorithm for solving block banded Toeplitz systems with banded Toeplitz blocks," in Proceedings of the 2001 IEEE International Conference on Acoustics, Speech, and Signal Processing, vol. 3, pp. 3325-3328, May 2002.

S. J. Reeves and Y. Gao, "Reduced k-space sampling for MR images with a limited region of support," in IEEE International Symposium on Biomedical Imaging, pp.733-736, July 2002. (Technique developed for PMMW array dithering and applied to an MRI problem.)

S. J. Reeves, "Fast and Direct Image Restoration With Edge-Preserving Regularization," 2002 IEEE DSP Workshop, (Pine Mtn., GA), October 2002.

R. Pan and S. J. Reeves, "Fast restoration and superresolution with edge-preserving regularization," in SPIE Vol. 4719 -- Infrared and Passive Millimeter-Wave Imaging Systems: Design, Analysis, Modeling, and Testing (R. Appleby, ed.), (Orlando, FL), SPIE - Int. Soc. Opt. Eng. (US), April 2003.

S. J. Reeves, "Fast Image Restoration Without Boundary Artifacts," submitted to IEEE Transactions on Image Processing.

R. Pan and S. J. Reeves, "Accelerated algorithm for image restoration with edge-preserving smoothing penalty," journal paper in preparation.

R. Pan and S. J. Reeves, "Fast algorithm for solving block banded Toeplitz systems with banded Toeplitz blocks," journal paper in preparation.

S. J. Reeves and Y. Gao, "Reduced k-space sampling for MR images with a limited region of support," journal paper in preparation (Technique developed for PMMW array dithering and applied to an MRI problem.)

6. Interactions/Transitions

6.1 Conference Presentations

Presentation at SPIE Aerosense: PMMW Imaging Systems, April 2002.

Presentation at SPIE Aerosense: PMMW Imaging Systems, April 2003.

Presentation at IEEE DSP Workshop, October 2002.

6.2 Transitions

None to date.

7. Patent Disclosures

None to date.